

Limits on variations of the fine-structure constant with gravitational potential from white-dwarf spectra

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We propose a new probe of the variation of the fine structure constant, α , in a strong gravitational field using metal lines in the spectra of white dwarf stars. Comparison of laboratory spectra with far-UV astronomical spectra from the white dwarf star G191-B2B recorded by the Hubble Space Telescope Imaging Spectrograph gives limits of $\Delta\alpha/\alpha = (4.2 \pm 1.6) \times 10^{-5}$ and $(-6.1 \pm 5.8) \times 10^{-5}$ from Fe V and Ni V spectra, respectively, at a dimensionless gravitational potential relative to Earth of $\Delta\phi \approx 5 \times 10^{-5}$. With better determinations of the laboratory wavelengths of the lines employed these results could be improved by up to two orders of magnitude.

Light scalar fields can appear very naturally in modern cosmological models and theories of high-energy physics, changing parameters of the Standard Model such as fundamental coupling constants and mass ratios. Like the gravitational charge, the scalar charge is purely additive, so near massive objects such as white dwarfs the effect of the scalar field can change. For objects that are not too relativistic, like stars and planets, both the total mass and the total scalar charge are simply proportional to the number of nucleons in the object. However, different types of coupling between the scalar field and other fields can lead to an increase or decrease in scalar coupling strengths near gravitating massive bodies [1]. For small variations, the scalar field variation at distance r from such an object of mass M is proportional to the change in dimensionless gravitational potential $\phi = GM/rc^2$, and we express this proportionality by introducing the sensitivity parameter, k_α [2]. Specifically, for variations in the fine structure ‘constant’, α , we write

$$\Delta\alpha/\alpha \equiv \frac{\alpha(r) - \alpha_0}{\alpha_0} \equiv k_\alpha \Delta\phi = k_\alpha \Delta \left(\frac{GM}{rc^2} \right).$$

This variation can be seen explicitly in particular theories of varying α , like those of Bekenstein [3] and Barrow-Sandvik-Magueijo [4], and their generalisations [5], where α can increase ($\Delta\alpha/\alpha > 0$) or decrease ($\Delta\alpha/\alpha < 0$) on approach to a massive object depending on the balance between electrostatic and magnetic energy in the ambient matter fields [1]. The most sensitive current limits on k_α come from measurements of two Earth-bound clocks over the course of a year [2, 6–11]. The sensitivity is entirely due to ellipticity in the Earth’s orbit, which gives

a 3% seasonal variation in the gravitational potential at the Earth due to the Sun. The peak-to-trough sinusoidal change in the potential has magnitude $\Delta\phi = 3 \times 10^{-10}$. Each clock has a different sensitivity to α -variation, and so $\Delta\alpha/\alpha$ can be measured and hence k_α extracted.

Due to the high precision of atomic clocks, k_α is determined very precisely despite the relatively small seasonal change in the gravitational potential. By contrast, we examine a ‘medium strength’ field, where $\Delta\phi$ is five orders of magnitude larger than in the Earth-bound experiments, and the distance between the probe and the source is $\sim 10^4$ times smaller than 1 AU. This allows us to probe nonlinear coupling of $\Delta\alpha/\alpha$ on $\Delta\phi$, or the effects of a scalar charge Q which produces a Yukawa-like scalar field $\Phi = Qe^{-mr}/r$ where m is the (very small) mass of the scalar.

In this work we use the high-resolution far-UV spectrum of the nearby (≈ 45 pc [13]), hot hydrogen-rich (DA) white dwarf G191-B2B, recorded by the Hubble Space Telescope Imaging Spectrograph (STIS), which contains several hundred absorption lines identified as Fe V and Ni V transitions [14]. These iron and nickel ions reside in the atmosphere of the white dwarf and the observed features are formed in its outer layers, near the surface of white dwarf. Consequently, the ions experience the strong downward surface gravity of the star, $\log g = 7.35 \pm 0.09$, but are supported against this by the transfer of momentum from high-energy photons, a process termed “radiative levitation” [15]. Here $g = GM/R^2$ in cgs units, with $M_{\text{WD}} = 0.51 M_\odot$ and $R_{\text{WD}} = 0.022 R_\odot$ [14]. The gravitational potential for ions in the atmosphere of this white dwarf relative to the

laboratory is $\Delta\phi \approx 5 \times 10^{-5}$.

To extract dependence on any α variation we first calculate the sensitivity coefficient for each line. As in previous work, we parameterize the sensitivity of the transition frequency to a variation in α from the laboratory value α_0 by the q -coefficient, defined in terms of the line frequency ω by

$$q = \left. \frac{d\omega}{dx} \right|_{x=0}, \quad (1)$$

where $x \equiv (\alpha/\alpha_0)^2 - 1 \approx 2\Delta\alpha/\alpha$ is the fractional (small) change in α^2 . The frequencies of lines that are observed in the white dwarf spectra are shifted from their laboratory values, ω_0 , due to the sum of Doppler and gravitational redshifts, z , and any potential α variation near the white dwarf:

$$1 + z = \frac{\omega_0 + qx}{\omega}.$$

The relationship between the laboratory wavelengths and those observed near the white dwarf is

$$\frac{\Delta\lambda}{\lambda_0} = \frac{\lambda - \lambda_0}{\lambda_0} = z - Q_\alpha \frac{\Delta\alpha}{\alpha} (1 + z), \quad (2)$$

where $Q_\alpha = 2q/\omega_0$ is the relative sensitivity of the transition frequency to variation in α . In Fig. 1 we present a graph of $\Delta\lambda/\lambda$ vs. Q_α for both Fe V lines (blue circles) and Ni V lines (red squares). The data used to generate these graphs can be found in Tables I and II.

To determine the sensitivity coefficients, q , for each line, we perform an *ab initio* calculation of the spectrum for $x = -0.01, 0.0$, and 0.01 , and then extract q using (1). The spectrum is calculated using the CI+MBPT method [16], a combination of configuration-interaction and many-body perturbation theory. Details of the implementation can be found in [17–19]. Here, we outline only the important points and defer details to a later work. The final q values are presented in Tables I and II for Fe V and Ni V, respectively.

For both Fe V and Ni V we start with a Dirac-Fock calculation in the V^N potential (i.e. the self-consistent field of all electrons) including the valence configuration $3d^n$ where $n = 4$ for Fe V and $n = 6$ for Ni V. In this procedure we simply scale the Dirac-Fock potential of the filled $3d^{10}$ shell by the number of valence electrons. We then form a B -spline basis by diagonalizing a set of splines over the self-consistent potential, which we use to form configurations with specified total angular momenta for our configuration interaction (CI) calculation. Configurations are formed by taking single and double excitations from the leading configurations $3d^n$, $3d^{n-1}4s$ and $3d^{n-1}4p$. In the case of Fe V we use a B -spline basis of size $11spdf7g$ and include all single and double excitations from the leading configurations. The resulting energy levels are sufficiently close (within $\sim 2\%$) to the available data [20].

For Ni V, the number of valence orbitals used for the CI calculation is markedly smaller. We include single-electron excitations to $12spdf$ and double excitations up to $5spdf$ from the leading configurations (a similar strategy was used for Cr II in [21]). Results using all single and double excitations to $7s6pdf$ were consistent, although the final energies were not as good. Many-body perturbation theory (MBPT) corrections using a valence basis of $30spdfgh$ were then added to the CI calculations, which improve the overall agreement with the experimental values (again level energies are within $\sim 2\%$). Note that while the q values themselves do not change very much with the addition of MBPT corrections for either ion, the energy levels are much better and this helps with their identification.

The Hubble Space Telescope (HST) STIS spectrum utilized in this work is unique in coupling the highest signal-to-noise so far achieved for any white dwarf with the best spectral resolution and spectral coverage available with the instrument. The spectrum is constructed from a series of high-resolution (resolving power $R \approx 144,000$) observations obtained with the E140H and E230H gratings as part of an extensive calibration programme for the instrument, designed to provide flux calibration at the 1% level for all E140H and E230H primary and secondary echelle grating modes [22]. The detailed list of observations and their reduction, merging and co-adding the components, has been reported by [14].

In summary, the outcome of this work was two single continuous spectra spanning the wavelength ranges 1160–1680Å and 1625–3145Å for E140H and E230H respectively. The signal-to-noise is typically ≈ 50 but exceeds 100 at some wavelengths.

These spectra contain almost 1000 absorption features, mostly in the 1160–1680Å region. Cross-correlating their measured wavelengths with lines from the Kurucz [23] and Kentucky [24] lists yields 914 identifications. A large number of these correspond to Fe V and Ni V transitions. The detailed identification work has been reported by [14].

Fe V: Of the original 106 Fe V transitions identified in the HST spectra, there are 96 for which there are good laboratory wavelengths (taken from [25]). Ref. [25] estimate an uncertainty of 0.004Å in their measurements, which dominates the errors for each value of $\Delta\lambda/\lambda$. From Fig. 1 we extract $\Delta\alpha/\alpha = (4.2 \pm 1.6) \times 10^{-5}$ (an apparent 2.6σ deviation from zero).

It is interesting to note that statistically the laboratory errors seem to be overestimated. Simply comparing the laboratory wavelengths with the HST data suggests that the actual error in the laboratory data is ~ 3 mÅ, rather than the claimed 4 mÅ. An unweighted fit from Fig. 1 gives $\Delta\alpha/\alpha = (4.3 \pm 1.2) \times 10^{-5}$.

One potential source of systematic error is the calibration of the laboratory measurements or the astronomical data. Offset errors will not affect our result, since this

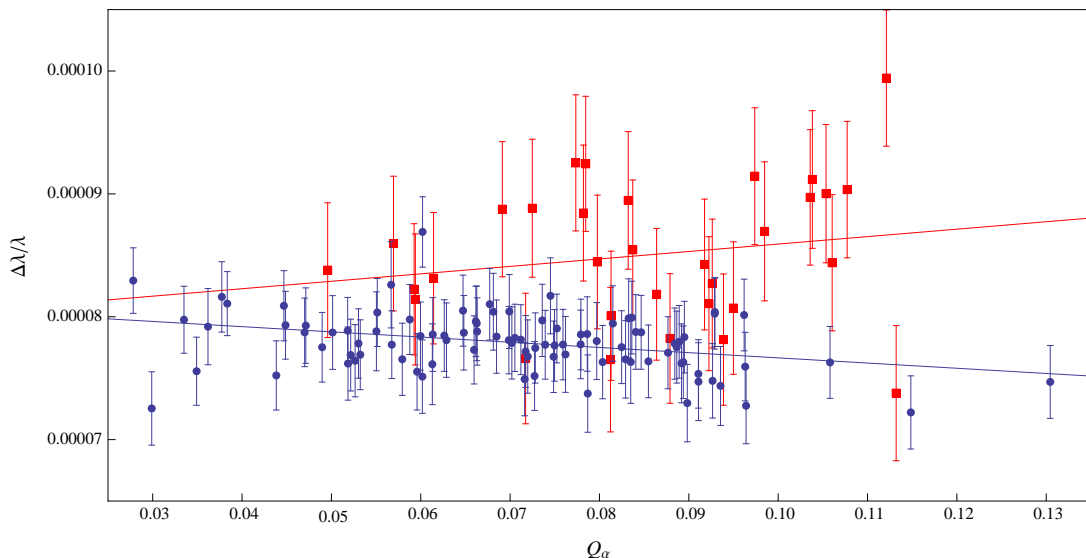


FIG. 1. $\Delta\lambda/\lambda$ vs. Q_α for transitions in Fe V (blue circles) and Ni V (red squares). The slope of the lines give $\Delta\alpha/\alpha = (4.2 \pm 1.6) \times 10^{-5}$ and $(-6.1 \pm 5.8) \times 10^{-5}$ for Fe V and Ni V, respectively.

simply causes a change in the measured doppler shift, z . On the other hand gain calibration errors — a linear mapping between the real and the measured λ — *could* cause a spurious α -variation *if* there is also a correlation between Q_α and λ . If there is no correlation, then any gain error would not matter since the data points would be completely randomised on the Q_α -axis.

In fact, such a correlation does exist. Energy levels of an ion that have a larger binding energy tend to spend more time closer to the nucleus, and therefore have larger relativistic effects. Therefore higher energy transitions (smaller λ) will tend to have a larger difference in the relativistic effects between the upper and lower levels, and hence have larger q . The correlation between q and λ_0 is -0.45 for the Fe V lines used (there is no evidence of non-linear correlations). Therefore, gain shift in the laboratory measurements or the calibration of the HST spectrograph would be a possible source of error.

We can account for the potentially spurious α -variation that may occur by first removing any linear dependence of $\Delta\lambda/\lambda$ on λ (see Fig. 2). The line of best fit for Fe V (blue) in Fig. 2 is $(\Delta\lambda/\lambda)_{\text{model}} = 7.79 \times 10^{-5} + 1.25 \times 10^{-8}(\lambda_0 - 1394 \text{ \AA})$. Here, the first term (see eq.(2)), $z_{\text{abs}} = 7.79 \times 10^{-5}$, is the average total redshift of the Fe V lines. The fitted model values, $(\Delta\lambda/\lambda)_{\text{model}}$ as a function of λ_0 , are removed from the observed values of $\Delta\lambda/\lambda$ and we plot these against Q_α to obtain a new value of $\Delta\alpha/\alpha = (2.8 \pm 1.6) \times 10^{-5}$, consistent with zero at the 1.77σ level (although again we note that if we reduce the assumed laboratory errors to the level suggested by the data, the error in $\Delta\alpha/\alpha$ is of order 1.2×10^{-5}). Note that while we have removed the potential systematic due to calibration error, we have also potentially lost a real signal of $\Delta\alpha/\alpha$. Ultimately, well calibrated laboratory and

astronomical data will remove the need for this procedure and boost the sensitivity of this method.

Ni V: Laboratory data for Ni V is provided by [26], who estimate their uncertainty as $\sim 1 \text{ m\AA}$ [27]. In fact, based on comparison with the HST data, this seems likely to be an underestimate. In Fig. 1 we use an assumed laboratory error of 7 m\AA , which leads to a more realistic distribution of residuals. Calculations for Ni V are also more difficult than for Fe V, and in several cases potentially useful transitions were not used because the levels could not be uniquely identified in our calculations. In other cases the original lab data were blended (which, aside from being flagged in [26], lead to obvious $> 3\sigma$ outliers in Fig. 1). In total, 32 Ni V transitions were used out of the 44 identified in HST spectra. The slope of the line in Fig. 1 gives a value of $\Delta\alpha/\alpha = (-6.1 \pm 5.8) \times 10^{-5}$, consistent with zero at the 1.05σ level.

As we did for Fe V, we removed any potential gain-shift systematic by subtracting the linear dependence of $\Delta\lambda/\lambda$ on λ : $(\Delta\lambda/\lambda)_{\text{model}} = 8.51 \times 10^{-5} - 8.77 \times 10^{-8}(\lambda_0 - 1283 \text{ \AA})$ (red line in Fig. 2). Note that for Ni V the slope is in the opposite direction to that of Fe V and is much larger (that is, $\Delta\lambda/\lambda$ tends to be smaller in transitions with longer wavelengths). Plotting $\Delta\lambda/\lambda - (\Delta\lambda/\lambda)_{\text{model}}$ against Q_α gives a line of best fit $\Delta\alpha/\alpha = (-2.5 \pm 5.8) \times 10^{-5}$, within 0.4σ of zero.

The weighted mean of the two values for $\Delta\alpha/\alpha$ we have obtained (without subtraction of the possible gain shift) is $\Delta\alpha/\alpha = (3.5 \pm 1.5) \times 10^{-5}$, which is dominated by the Fe V result and consistent with the Ni V result at 1.6σ . We can compare the limits on α variation achieved in this system with the application of the many-multiplet method to a quasar absorption system [28, 29], which typically are at the $\Delta\alpha/\alpha \sim O(10^{-5})$ level. Firstly, we

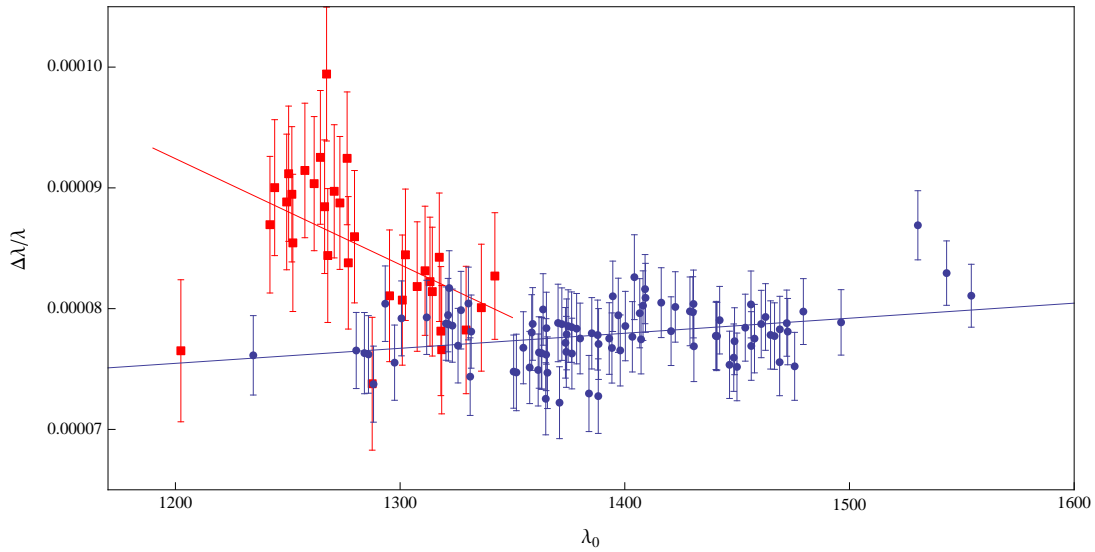


FIG. 2. $\Delta\lambda/\lambda$ vs. λ_0 for transitions in Fe V (blue circles) and Ni V (red squares). The correlation seen here could be due to calibration systematics, or α -variation since Q_α and λ_0 are (anti-)correlated.

are using ~ 100 lines, rather than ~ 10 , per system used in quasar studies. This gives us a statistical advantage over the quasar studies. Secondly, the q values are much larger here since we are using more highly ionised species. Taken together, this study should have more than an order-of-magnitude higher sensitivity per system than the quasar studies, and we should be reaching statistical accuracies below 10^{-6} . Unfortunately, at present we are limited by relatively poor laboratory wavelengths. In the future, this limitation may be circumvented by comparing two white dwarfs, or comparison with improved laboratory (or solar) spectra. New measurements of the Fe V and Ni V spectra could improve the limit by up to two orders of magnitude.

It is interesting to note that the gravitational redshift, $z = \Delta\phi \approx 5 \times 10^{-5}$, is the dominant contribution to the average total redshift, $z_{abs} = 7.78 \times 10^{-5}$ for Fe V and 8.47×10^{-5} for Ni V. With improvement in laboratory wavelengths, this system should also be able to provide a test of the equivalence principle of General Relativity in a ‘medium strength’ field with higher accuracy and provide constraints on other variations of traditional ‘constants’ driven by scalar fields in the universe [1, 30, 31].

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TABLE I: Laboratory and astronomically observed lines in Fe V. Laboratory wavelengths are taken from [25] and have an estimated uncertainty of ~ 4 mÅ. Observed wavelengths have a measurement uncertainty $\delta\lambda_{\text{obs}}$.

λ_{lab} (Å)	λ_{obs} (Å)	$\delta\lambda_{\text{obs}}$ (mÅ)	Lower Level	Upper Level	q (cm ⁻¹)		
1234.648	1234.742	0.7	$3d^3(^4P)4s$	3P_2	$3d^3(^4P)4p$	$^3S_1^o$	2484
1280.471	1280.569	0.5	$3d^3(^2G)4s$	3G_5	$3d^3(^2D_2)4p$	$^3F_4^o$	3238
1284.109	1284.207	1.6	$3d^3(^4P)4s$	5P_1	$3d^3(^4P)4p$	$^5S_2^o$	3251
1285.918	1286.016	1.0	$3d^3(^4P)4s$	3P_1	$3d^3(^2D_2)4p$	$^3P_1^o$	3468
1288.169	1288.264	0.7	$3d^3(^4P)4s$	5P_2	$3d^3(^4P)4p$	$^5S_2^o$	3054
1293.377	1293.481	0.6	$3d^3(^2G)4s$	3G_3	$3d^3(^2D_2)4p$	$^3F_2^o$	2634
1297.547	1297.645	0.6	$3d^3(^4P)4s$	5P_3	$3d^3(^4P)4p$	$^5S_2^o$	2296
1300.608	1300.711	0.5	$3d^3(^4P)4s$	5P_3	$3d^3(^2P)4p$	$^1D_2^o$	1391
1311.828	1311.932	0.5	$3d^3(^2P)4s$	1P_1	$3d^3(^2D_2)4p$	$^1D_2^o$	1797
1320.410	1320.514	0.3	$3d^3(^2H)4s$	3H_4	$3d^3(^2H)4p$	$^3G_3^o$	3183
1321.341	1321.446	0.4	$3d^3(^2G)4s$	3G_4	$3d^3(^2H)4p$	$^3H_5^o$	2508
1321.490	1321.594	0.3	$3d^3(^2G)4s$	3G_5	$3d^3(^2H)4p$	$^3H_6^o$	2453
1321.850	1321.958	0.8	$3d^3(^2H)4s$	3H_4	$3d^3(^2H)4p$	$^3G_4^o$	2819
1323.269	1323.373	0.3	$3d^3(^2H)4s$	3H_5	$3d^3(^2H)4p$	$^3G_4^o$	2971
1325.781	1325.883	0.9	$3d^3(^2H)4s$	3H_5	$3d^3(^2H)4p$	$^3G_5^o$	2874
1327.101	1327.207	1.5	$3d^3(^2D_2)4s$	1D_2	$3d^3(^2P)4p$	$^1P_1^o$	3137
1330.401	1330.508	0.2	$3d^3(^2H)4s$	3H_6	$3d^3(^2H)4p$	$^3G_5^o$	2627
1331.185	1331.284	1.5	$3d^3(^2D_2)4s$	3D_1	$3d^3(^2D_2)4p$	$^3P_0^o$	3514
1331.640	1331.744	0.5	$3d^3(^2D_2)4s$	1D_2	$3d^3(^2D_2)4p$	$^1D_2^o$	2361
1350.535	1350.636	0.9	$3d^3(^4P)4s$	3P_1	$3d^3(^4P)4p$	$^3D_2^o$	3430
1351.755	1351.856	1.5	$3d^3(^4F)4s$	5F_1	$3d^3(^4F)4p$	$^3D_2^o$	3369
1354.847	1354.951	0.6	$3d^3(^2F)4s$	1F_3	$3d^3(^2F)4p$	$^1F_3^o$	2656
1357.675	1357.777	0.7	$3d^3(^2F)4s$	3F_4	$3d^3(^2F)4p$	$^3D_3^o$	2216
1358.567	1358.673	1.5	$3d^3(^2D_2)4s$	3D_1	$3d^3(^2D_2)4p$	$^3D_2^o$	2933
1359.006	1359.113	0.8	$3d^3(^2D_1)4s$	3D_3	$3d^3(^2D_1)4p$	$^3F_4^o$	3115
1361.447	1361.549	0.7	$3d^3(^2F)4s$	1F_3	$3d^3(^2F)4p$	$^1G_4^o$	2630
1361.825	1361.929	0.5	$3d^3(^2F)4s$	3F_4	$3d^3(^2F)4p$	$^3G_5^o$	3138
1362.864	1362.968	0.7	$3d^3(^2D_2)4s$	3D_3	$3d^3(^2D_2)4p$	$^3D_3^o$	2948
1363.077	1363.181	0.5	$3d^3(^4F)4s$	5F_3	$3d^3(^4F)4p$	$^5F_4^o$	3279
1363.642	1363.751	0.5	$3d^3(^4F)4s$	5F_4	$3d^3(^4F)4p$	$^5F_5^o$	3066
1364.824	1364.923	0.8	$3d^3(^4F)4s$	5F_2	$3d^3(^4F)4p$	$^3D_1^o$	1095
1364.984	1365.088	0.7	$3d^3(^2F)4s$	3F_2	$3d^3(^2F)4p$	$^3D_3^o$	1900
1365.115	1365.222	0.7	$3d^3(^4F)4s$	5F_3	$3d^3(^4F)4p$	$^3D_2^o$	2508
1365.571	1365.673	0.6	$3d^3(^4F)4s$	5F_2	$3d^3(^4F)4p$	$^5F_3^o$	4776
1370.303	1370.411	1.8	$3d^3(^2H)4s$	3H_6	$3d^3(^2H)4p$	$^1H_5^o$	2008
1370.947	1371.046	0.8	$3d^3(^4F)4s$	5F_1	$3d^3(^4F)4p$	$^5F_2^o$	4189
1371.987	1371.046	0.8	$3d^3(^2D_2)4s$	3D_1	$3d^3(^2D_2)4p$	$^3D_1^o$	1827
1373.587	1373.693	0.3	$3d^3(^4F)4s$	5F_4	$3d^3(^4F)4p$	$^5F_4^o$	2611
1373.967	1374.072	0.5	$3d^3(^4P)4s$	3P_2	$3d^3(^4P)4p$	$^3D_3^o$	1916
1374.116	1374.223	0.5	$3d^3(^2F)4s$	3F_3	$3d^3(^2F)4p$	$^3G_4^o$	2554
1374.789	1374.897	1.0	$3d^3(^2D_1)4s$	3D_2	$3d^3(^2D_1)4p$	$^3F_3^o$	2231
1376.337	1376.445	0.3	$3d^3(^4F)4s$	5F_5	$3d^3(^4F)4p$	$^5F_5^o$	2275
1376.455	1376.560	0.5	$3d^3(^4F)4s$	5F_2	$3d^3(^4F)4p$	$^5F_2^o$	3843
1378.560	1378.668	0.3	$3d^3(^4P)4s$	5P_3	$3d^3(^4P)4p$	$^5D_4^o$	3246
1380.112	1380.219	0.6	$3d^3(^4F)4s$	5F_1	$3d^3(^4F)4p$	$^5D_1^o$	3212

TABLE I: Fe V lines – *Continued from previous page*

λ_{lab} (Å)	λ_{obs} (Å)	$\delta\lambda_{\text{obs}}$ (mÅ)	Lower Level	Upper Level	q (cm ⁻¹)
1384.055	1384.156	1.7	$3d^3(^2P)4s$	3P_1 $3d^3(^4P)4p$	$^3D_2^o$ 3245
1385.313	1385.421	0.9	$3d^3(^4F)4s$	5F_1 $3d^3(^4F)4p$	$^5D_0^o$ 3209
1387.938	1388.046	0.4	$3d^3(^2H)4s$	3H_6 $3d^3(^2H)4p$	$^3I_7^o$ 3186
1388.195	1388.296	1.5	$3d^3(^4P)4s$	5P_1 $3d^3(^4P)4p$	$^3P_1^o$ 3472
1388.328	1388.435	0.8	$3d^3(^4P)4s$	5P_1 $3d^3(^4P)4p$	$^5D_2^o$ 3157
1393.073	1393.181	1.0	$3d^3(^4P)4s$	5P_2 $3d^3(^4P)4p$	$^5D_2^o$ 2960
1394.272	1394.379	0.6	$3d^3(^2G)4s$	3G_4 $3d^3(^2G)4p$	$^3F_3^o$ 2685
1394.665	1394.778	0.7	$3d^3(^2G)4s$	3G_3 $3d^3(^2G)4p$	$^3F_2^o$ 2428
1397.106	1397.217	1.6	$3d^3(^2P)4s$	3P_1 $3d^3(^2P)4p$	$^3S_1^o$ 2917
1397.972	1398.079	0.9	$3d^3(^4P)4s$	5P_3 $3d^3(^4P)4p$	$^5D_3^o$ 2072
1400.243	1400.353	0.4	$3d^3(^4F)4s$	3F_2 $3d^3(^4F)4p$	$^3F_2^o$ 2782
1403.370	1403.479	0.8	$3d^3(^4F)4s$	3F_3 $3d^3(^4F)4p$	$^3F_3^o$ 2671
1404.260	1404.376	2.9	$3d^3(^4P)4s$	3P_0 $3d^3(^2P)4p$	$^3D_1^o$ 2018
1406.669	1406.781	0.5	$3d^3(^4F)4s$	3F_4 $3d^3(^4F)4p$	$^3F_4^o$ 2352
1407.248	1407.357	0.4	$3d^3(^2H)4s$	1H_5 $3d^3(^2H)4p$	$^1I_6^o$ 2587
1408.117	1408.230	0.7	$3d^3(^4F)4s$	5F_1 $3d^3(^4F)4p$	$^5F_2^o$ 3299
1409.026	1409.141	0.5	$3d^3(^4F)4s$	5F_3 $3d^3(^4F)4p$	$^5D_2^o$ 1339
1409.220	1409.334	0.4	$3d^3(^4F)4s$	5F_4 $3d^3(^4F)4p$	$^5D_3^o$ 1585
1416.219	1416.333	0.9	$3d^3(^2D_2)4s$	1D_2 $3d^3(^2D_2)4p$	$^1F_3^o$ 2285
1420.602	1420.713	0.6	$3d^3(^2G)4s$	3G_4 $3d^3(^2G)4p$	$^3G_4^o$ 2506
1422.481	1422.595	1.1	$3d^3(^2P)4s$	3P_1 $3d^3(^2P)4p$	$^3D_2^o$ 3381
1429.004	1429.118	0.7	$3d^3(^2G)4s$	3G_5 $3d^3(^2G)4p$	$^3G_4^o$ 2057
1430.309	1430.423	1.3	$3d^3(^2F)4s$	1F_3 $3d^3(^2F)4p$	$^1D_2^o$ 2573
1430.573	1430.688	0.4	$3d^3(^4F)4s$	5F_5 $3d^3(^4F)4p$	$^5G_6^o$ 3247
1430.751	1430.861	1.2	$3d^3(^2D_2)4s$	3D_3 $3d^3(^4P)4p$	$^3D_3^o$ 1823
1440.528	1440.640	0.4	$3d^3(^4F)4s$	5F_4 $3d^3(^4F)4p$	$^5G_5^o$ 2704
1440.792	1440.904	1.0	$3d^3(^4P)4s$	5P_1 $3d^3(^4P)4p$	$^5P_2^o$ 1635
1441.049	1441.161	0.5	$3d^3(^4P)4s$	5P_3 $3d^3(^4P)4p$	$^5P_3^o$ 2565
1442.221	1442.335	0.5	$3d^3(^2G)4s$	1G_4 $3d^3(^2G)4p$	$^1H_5^o$ 2608
1446.618	1446.727	0.5	$3d^3(^2G)4s$	3G_5 $3d^3(^2G)4p$	$^3H_6^o$ 3148
1448.494	1448.604	0.6	$3d^3(^2G)4s$	1G_4 $3d^3(^2G)4p$	$^1F_3^o$ 3324
1448.846	1448.958	0.40	$3d^3(^4F)4s$	5F_3 $3d^3(^4F)4p$	$^5G_4^o$ 2277
1449.928	1450.037	0.7	$3d^3(^2F)4s$	3F_4 $3d^3(^2F)4p$	$^3F_4^o$ 2508
1453.618	1453.732	0.5	$3d^3(^2H)4s$	1H_5 $3d^3(^2H)4p$	$^1H_5^o$ 2063
1456.161	1456.278	0.5	$3d^3(^4F)4s$	5F_2 $3d^3(^4F)4p$	$^5G_3^o$ 1893
1456.285	1456.397	1.1	$3d^3(^4P)4s$	5P_2 $3d^3(^4P)4p$	$^5P_1^o$ 1828
1457.727	1457.840	1.0	$3d^3(^4P)4s$	5P_3 $3d^3(^4P)4p$	$^5P_2^o$ 1679
1460.726	1460.841	0.8	$3d^3(^4F)4s$	5F_4 $3d^3(^4F)4p$	$^5G_4^o$ 1609
1462.631	1462.747	0.5	$3d^3(^4F)4s$	5F_1 $3d^3(^4F)4p$	$^5G_2^o$ 1534
1464.876	1464.990	1.1	$3d^3(^2F)4s$	3F_2 $3d^3(^2F)4p$	$^3F_2^o$ 1810
1466.649	1466.763	0.6	$3d^3(^2G)4s$	3G_4 $3d^3(^2G)4p$	$^3H_5^o$ 1935
1468.911	1469.022	0.8	$3d^3(^4F)4s$	5F_2 $3d^3(^4F)4p$	$^5G_2^o$ 1188
1469.000	1469.115	0.4	$3d^3(^2H)4s$	3H_6 $3d^3(^2H)4p$	$^3H_6^o$ 2401
1472.098	1472.214	0.5	$3d^3(^2H)4s$	3H_5 $3d^3(^2H)4p$	$^3H_5^o$ 2252
1472.512	1472.627	0.6	$3d^3(^2H)4s$	3H_4 $3d^3(^2H)4p$	$^3H_4^o$ 2372
1475.604	1475.715	1.1	$3d^3(^2G)4s$	3G_5 $3d^3(^2G)4p$	$^3H_5^o$ 1485
1479.471	1479.589	0.5	$3d^3(^2G)4s$	3G_4 $3d^3(^2G)4p$	$^3H_4^o$ 1132
1496.266	1496.384	0.7	$3d^3(^2G)4s$	1G_4 $3d^3(^2G)4p$	$^3F_4^o$ 1732
1530.439	1530.572	1.8	$3d^3(^2D_2)4s$	1D_2 $3d^3(^2D_2)4p$	$^1P_1^o$ 1967
1543.234	1543.362	1.0	$3d^3(^4F)4s$	3F_2 $3d^3(^4F)4p$	$^3D_1^o$ 901
1554.219	1554.345	0.6	$3d^3(^4F)4s$	3F_4 $3d^3(^4F)4p$	$^3D_3^o$ 1234

TABLE II: Laboratory and astronomically observed lines in Ni V. Laboratory wavelengths are taken from [26] and we estimate their uncertainty at $\sim 7 \text{ m\AA}$. Observed wavelengths have a measurement uncertainty $\delta\lambda_{\text{obs}}$. Where q values have been omitted, they could not be unambiguously identified in the *ab initio* calculations. Where lines were blended in the laboratory data, they are marked with an asterisk in the λ_{lab} column.

λ_{lab} (Å)	λ_{obs} (Å)	$\delta\lambda_{\text{obs}}$ (mÅ)	Lower Level	Upper Level	q (cm $^{-1}$)
1202.423	1202.515	1.0	$3d^5(^4G)4s$ 5G_4	$3d^5(^4G)4p$ $^3F_3^o$	3378
1227.480	1227.635	0.3	$3d^5(^2F_1)4s$ 3F_4	$3d^5(^2H)4p$ $^3G_4^o$	
1232.801	1232.905	0.7	$3d^5(^2H)4s$ 1H_5	$3d^5(^2H)4p$ $^1H_5^o$	
1235.831	1235.936	0.5	$3d^5(^2I)4s$ 1I_6	$3d^5(^4F)4p$ $^5G_6^o$	
1242.072	1242.180	0.6	$3d^5(^2I)4s$ 1I_6	$3d^5(^2I)4p$ $^3H_5^o$	3964
1244.174	1244.286	0.2	$3d^5(^6S)4s$ 7S_3	$3d^5(^6S)4p$ $^7P_4^o$	4234
1249.520	1249.631	0.5	$3d^5(^4G)4s$ 5G_5	$3d^5(^4G)4p$ $^5F_4^o$	2901
1250.384	1250.498	0.2	$3d^5(^4G)4s$ 5G_6	$3d^5(^4G)4p$ $^5H_7^o$	4152
1251.821	1251.933	0.4	$3d^5(^4G)4s$ 3G_5	$3d^5(^4G)4p$ $^3G_5^o$	3324
1252.155*	1252.269	0.4	$3d^5(^4G)4s$ 5G_6	$3d^5(^4F)4p$ $^5F_5^o$	
1252.267	1252.374	1.3	$3d^5(^2I)4s$ 3I_6	$3d^5(^2I)4p$ $^3H_6^o$	3343
1254.187	1254.300	1.3	$3d^5(^2F_1)4s$ 1F_3	$3d^5(^2F_1)4p$ $^1D_2^o$	
1257.620	1257.735	0.2	$3d^5(^4G)4s$ 5G_5	$3d^5(^4G)4p$ $^5H_6^o$	3872
1261.330	1261.445	0.5	$3d^5(^2F_1)4s$ 3F_4	$3d^5(^2F_1)4p$ $^3G_5^o$	
1261.745	1261.859	0.3	$3d^5(^4D)4s$ 5D_4	$3d^5(^4D)4p$ $^5F_5^o$	4269
1264.518	1264.635	0.2	$3d^5(^4G)4s$ 5G_6	$3d^5(^4G)4p$ $^5H_5^o$	3059
1266.395	1266.507	0.3	$3d^5(^4G)4s$ 5G_4	$3d^5(^4G)4p$ $^5H_5^o$	3088
1266.859	1266.969	0.7	$3d^5(^4P)4s$ 5P_1	$3d^5(^4D)4p$ $^5P_2^o$	
1267.275	1267.401	0.6	$3d^5(^2I)4s$ 3I_6	$3d^5(^2I)4p$ $^3I_7^o$	4423
1267.803	1267.910	0.6	$3d^5(^2I)4s$ 3I_7	$3d^5(^2I)4p$ $^3I_7^o$	4182
1270.677	1270.791	0.3	$3d^5(^2I)4s$ 3I_7	$3d^5(^2I)4p$ $^3K_8^o$	4076
1273.198	1273.311	0.3	$3d^5(^4G)4s$ 5G_3	$3d^5(^4G)4p$ $^5H_4^o$	2715
1276.415	1276.533	0.5	$3d^5(^4D)4s$ 5D_3	$3d^5(^4D)4p$ $^5F_4^o$	3073
1276.945	1277.052	0.2	$3d^5(^6S)4s$ 7S_3	$3d^5(^6S)4p$ $^7P_2^o$	1942
1279.708	1279.818	0.4	$3d^5(^4G)4s$ 5G_2	$3d^5(^4G)4p$ $^5H_3^o$	2225
1282.247*	1282.309	0.9	$3d^5(^2I)4s$ 3I_6	$3d^5(^2I)4p$ $^3I_6^o$	2909
1282.247*	1282.383	0.8	$3d^5(^2I)4s$ 3I_5	$3d^5(^2I)4p$ $^3I_6^o$	3023
1287.576	1287.671	1.1	$3d^5(^2D_3)4s$ 3D_3	$3d^5(^2D_3)4p$ $^3F_4^o$	
1295.286	1295.391	0.9	$3d^5(^4P)4s$ 5P_3	$3d^5(^4G)4p$ $^5F_3^o$	3561
1298.733	1298.829	1.0	$3d^5(^2G_2)4s$ 3G_5	$3d^5(^2H)4p$ $^3I_6^o$	
1300.981	1301.086	0.4	$3d^5(^6S)4s$ 5S_2	$3d^5(^6S)4p$ $^5P_1^o$	3651
1302.380	1302.490	1.1	$3d^5(^4P)4s$ 5P_3	$3d^5(^4P)4p$ $^5S_2^o$	3062
1307.595	1307.702	0.3	$3d^5(^6S)4s$ 5S_2	$3d^5(^6S)4p$ $^5P_2^o$	3304
1310.249	1310.354	1.2	$3d^5(^4F)4s$ 3F_4	$3d^5(^4F)4p$ $^3G_5^o$	
1311.106	1311.215	0.4	$3d^5(^4G)4s$ 5G_5	$3d^5(^4G)4p$ $^5G_5^o$	2343
1313.303	1313.411	0.4	$3d^5(^4G)4s$ 5G_4	$3d^5(^4G)4p$ $^5G_4^o$	2256
1314.330	1314.437	0.4	$3d^5(^4G)4s$ 5G_3	$3d^5(^4G)4p$ $^5G_3^o$	2260
1317.436	1317.547	0.3	$3d^5(^2I)4s$ 1I_6	$3d^5(^2I)4p$ $^1K_7^o$	3483
1317.962	1318.080	0.9	$3d^5(^2F_1)4s$ 1F_3	$3d^5(^2F_1)4p$ $^3G_4^o$	
1318.148	1318.251	0.8	$3d^5(^4P)4s$ 5P_3	$3d^5(^4G)4p$ $^5F_3^o$	3561
1318.513	1318.614	0.3	$3d^5(^6S)4s$ 5S_2	$3d^5(^6S)4p$ $^5P_3^o$	2721
1329.372	1329.476	0.4	$3d^5(^4G)4s$ 3G_4	$3d^5(^4G)4p$ $^3H_5^o$	3306
1336.157	1336.264	0.6	$3d^5(^4G)4s$ 3G_5	$3d^5(^4G)4p$ $^3H_6^o$	3042
1342.177	1342.288	0.7	$3d^5(^4G)4s$ 3G_5	$3d^5(^4G)4p$ $^3F_4^o$	3450